Demonstration of Long Vacuum Integrity Lifetime of a Trapped-Ion Clock Package

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ABSTRACT. — A compact Hg ion trap package that has been vacuum-sealed since 2005 has been demonstrated to be successfully operational. This work shows the reliability of such units in view of next-generation ground and spaceborne trapped-ion clocks. The excellent vacuum property of the trap package allowed us to study charge transfer relaxation effects between neutral Hg and trapped Hg ions.

I. Introduction

Since the advent of the Global Positioning System (GPS), precise navigation has become an indispensable part of our day-to-day lives. Space-based navigation and deep-space tracking can be enhanced by precise onboard clocks. A promising avenue for future precision space clocks is the trapped Hg^+ standard [1,2]. An Hg^+ standard has several advantages over other compact standards approaches. For instance, it does not require lasers; therefore there is no complexity associated with operating and stabilizing lasers. The Hg ions in the trap are optically pumped by a spectral lamp as used in compact space rubidium clocks. An Hg^+ clock requires no shutters, has low magnetic field sensitivity and no wall collisions (as in rubidium vapor cell clocks) [3,4]. It is made of a completely sealed vacuum tube with no active pump, no consumables (as in cesium tube standards and hydrogen masers), no cryogenics, and no microwave cavities. The absence of wall-collisions and buffer gas broadening offers a high atomic line-Q.

In this article, we present a compact Hg ion quadrupole linear trap package (volume of 1 liter) that has been vacuum-sealed since 2005 (about 9.5 years). We report the long shelf life of a titanium vacuum tube and the improvement of the vacuum in a sealed system only by a passive getter pump. Furthermore, longer trap lifetimes of trapped ions in a quadrupole linear trap exceeding one year were measured. We also discuss an investigation on $Hg–Hg^+$ charge transfer phenomena.

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II. Brief History of the Trap Package

The quadrupole linear trap package used in the studies presented here was fabricated in May 2003. It was constructed as the first prototype of a completely sealable package. The construction and characterization of the clock package was reported in [5]. A brief history of the usage and evolution of this package relevant to this work is presented as follows:

- May 2003: Quadrupole assembly fabricated.
- July 2005: Quadrupole inserted into the trap/clock system.
- August 2005: First microwave clock signal observed.
- October 2005: Getter pump valve closed. The system has been sealed since then (~9 years).
- March 2007: Aluminum bell jar tests to simulate the space environment [6]. After the tests, the trap package was not maintained inside the vacuum jar.
- May 2011: System (trap and vacuum) last used; since then the system has been idle.

The optical and detection packages that were used in 2005 were retained with the package. The experiments on this sealed package were conducted from 2005 until 2011. The trapped-ion lifetime tests were reported in 2009 [6]. The lifetime up to six months was reported for this package. Since 2011, this vacuum tube package, the optical package, and the detection package have been in an idle state. They were operated again in November 2014 and the tests are reported in the following sections.

III. Experimental Setup

The physics package, which includes a quadrupole linear trap, optics components along with a ^{202}Hg discharge lamp, and the photomultiplier (PMT) detector is shown in Figure 1. This package was designed and fabricated in 2003 and the details were published in [5]. The main focus of this package design is to eliminate the use of active mechanical pumping and only use the passive getter pump to maintain low vacuum pressure. On the other hand, these getter pumps will not pump the noble buffer gases, thereby eliminating the need for a continuous supply of buffer gas that is necessary for cooling trapped ions. The essence of achieving the sealed package relies on better cleaning and high temperature (~400 deg C) baking. The trap rods are made of molybdenum (nonmagnetic) in order to get narrow clock transition (40-GHz) linewidths. The optical and detector packages are orthogonal to each other. The light source from a ^{202}Hg lamp is used for optical pumping of the trapped ions and the emitted ion fluorescence is collected using the PMT detector assembly. Each assembly has focusing lenses and dichroic mirrors (>95 percent reflectance for 194 nm and <10 percent reflectance for 254 nm). This helps in increasing the signal-to-noise (S/N) ratio. Further details of the optical and the detection packages are explained in [5]. This is a quadrupole linear trap package. Neon buffer gas of 1×10^{-5} Torr is filled into the vacuum package for cooling of trapped ions [7]. However, for our measurements presented in this article, we only use the quadrupole linear trap region, as we do not perform the clock stability measurements.

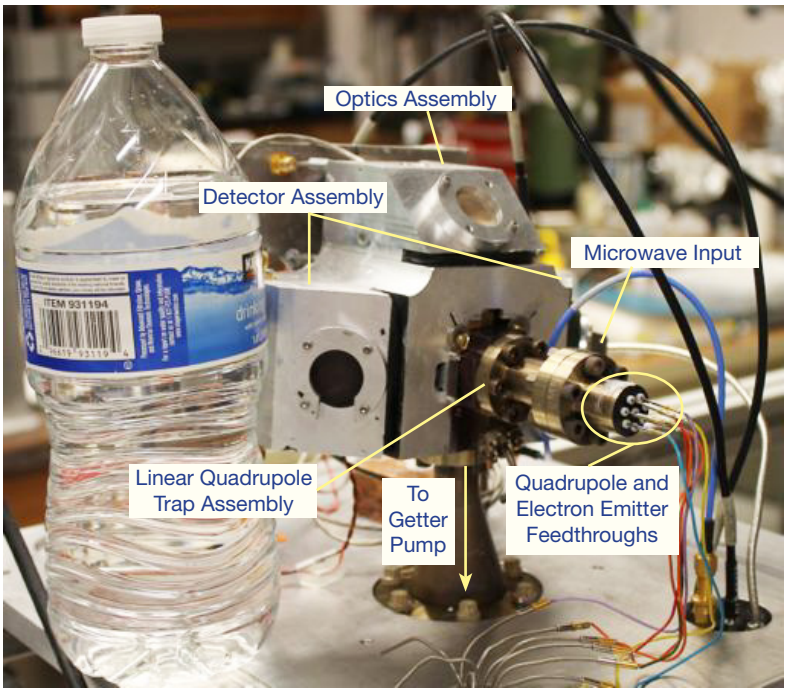

Figure 1. The 1-liter package showing the quadrupole linear trap feedthroughs and the electron emitter feedthroughs along with the optical and detection assemblies. A 1-liter water bottle is placed to give a size perspective.

IV. Experiment and Results

The sealed system was turned on in the following steps. First, the electron emitter was turned on and an emission current of 2.5 μA was measured, comparable to the previous values. This gave us an indication that the vacuum inside the package was intact. Following this, the ^{202}Hg discharge lamp was turned on and the neutral Hg fluorescence at 254 nm was measured by heating the getter to about 40 deg C. The getter heating was required as there was adsorption of neutral Hg on the getter medium. Once the neutral Hg fluorescence was seen, rf voltage (295 Vrms at 1.83 MHz on a single electrode) was applied to the quadrupole trap rods and the ion trapping signal was observed.

A. Lamp Optical Pumping Test

Optical pumping time of the Hg ions from a hyperfine ground state via an excited state gives an indication of 194-nm light intensity from the ^{202}Hg lamp [8] (also see ^{199}Hg and ^{202}Hg energy level diagrams for 194 nm interrogation in [8]). In our experiment, the pumping light was kept constant, but the microwave tuned to the resonance transition (~40.5 GHz) was switched on and off (cf. Figure 2). When the microwaves are switched on, the ions are making transitions from the lower ground state ($|^2S_{1/2}, F = 0\rangle$) to the higher ground state ($|^2S_{1/2}, F = 1\rangle$), giving rise to more fluorescence signal, as seen in Figure 2. When the microwaves are turned off, the 194-nm light from the lamp optically pumps the ions again to the lower ground state, via the excited state $^2P_{1/2}$. An optical pumping time of 4.7(2) s was measured (cf. Figure 2).

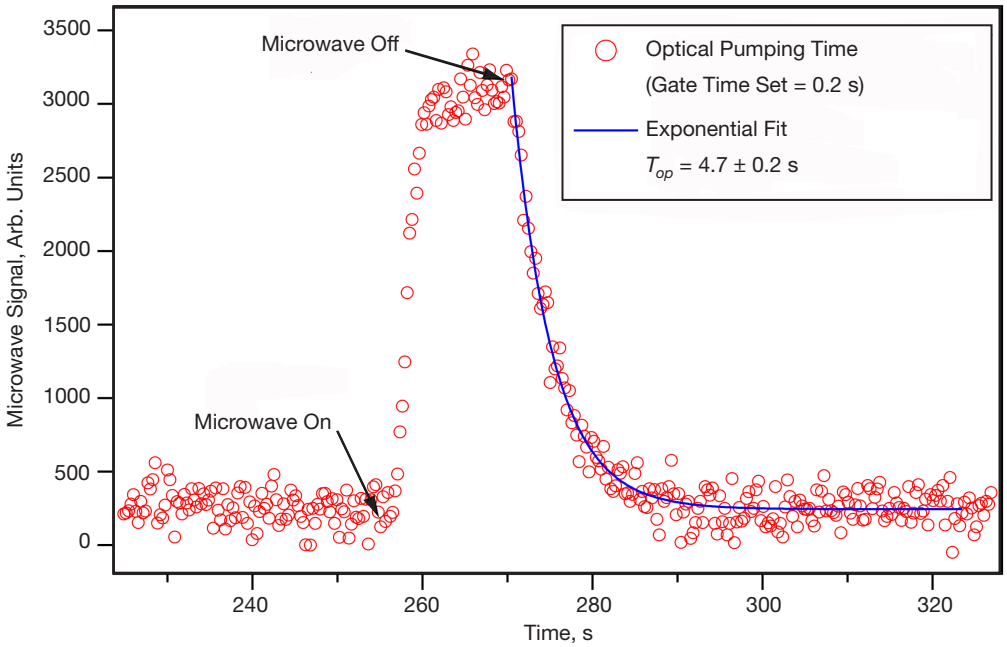

Figure 2. Optical pumping time measured by the method of switching the microwave interrogation. Measurement gate time of 0.2 s was used for better resolution. An optical pumping time of 4.7(2) s was measured.

B. Rabi Spectroscopy

The trapped ions are first optically pumped to the lower ground state by an optical pulse, and microwave interrogation then is performed in the dark state (i.e., when the pumping light is switched to the dim state) by stepping the microwave frequency for each measurement. Then the ion upper state population is detected by a short (or weaker) optical pulse; this is known as the Rabi interrogation method. Typically in our measurements, the optical pumping pulse time of 5 s and microwave pulse of 4 s with a power of –26 dBm were used. Typical Rabi curves obtained are shown in Figure 4 and Figure 5 (see page 6). Subhertz linewidths are obtained giving a line-Q of ~10^{11} with excellent S/N ratio. The line-Q and S/N for these resonances indicate excellent short-term stabilities of ~1.5×10^{-13}. $\tau^{-1/2}$. During these measurements, no magnetic shields were used to minimize the ambient magnetic fields and therefore clock transition was shifted from the unperturbed transition (40.507347996xx GHz) by a few tens of hertz [7].

C. Ion Cloud Lifetime

The main objective of this package design was to eliminate the need for an active mechanical pump. Therefore, as pointed out earlier, the physics package (metal tube, UV windows, ceramics, etc.) had to withstand the high-temperature bakeout, to be operated in a sealed state using only a getter pump. The use of getter pumps also helps in size reduction. The measurement of the trapped ions' lifetime was carried out by recording the amplitude of the clock signal after ion loading has been done. Such measurements in this package were demonstrated in [6]. With the electron filament off, the previously reported lifetime was 5000 hr, and with the same package, we have obtained lifetimes of about 9888 hr

(412 days). The previous results, along with newly measured lifetime data, are shown in Figure 3 (see Figure 3 notes). It is to be noted that these measurements are done without any replenishment of the ions. This demonstrates an improvement of the vacuum inside the tube over five more years, demonstrating sealed long vacuum integrity of our vacuum package and its longer shelf life.

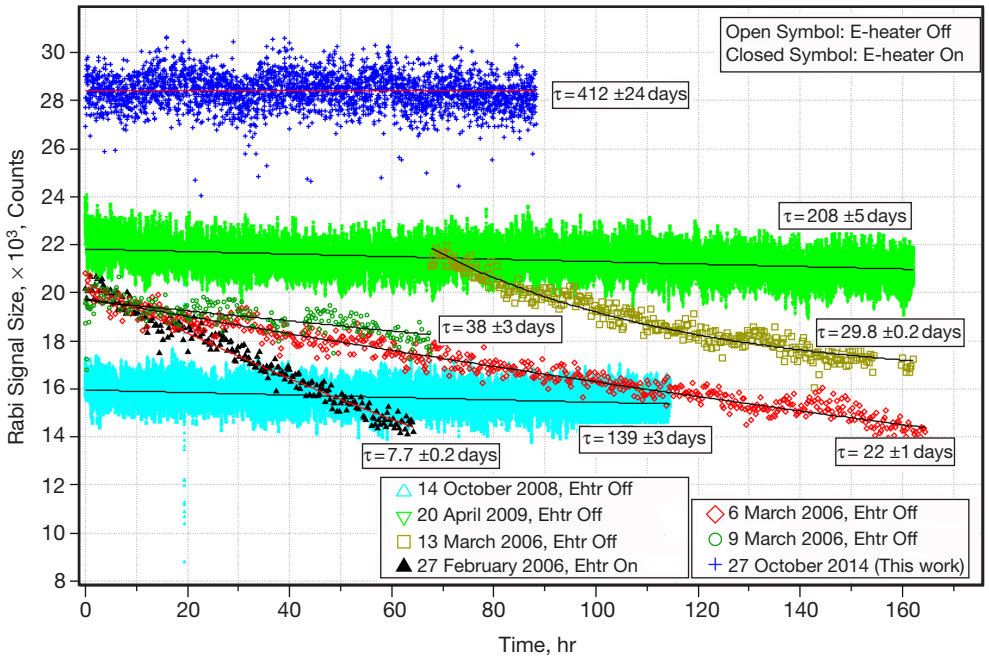

Figure 3. Trap lifetimes measured with the same vacuum trap package at different times showing improvement in the ion trap lifetime after seal-off of the vacuum trap tube since 2004. The four longest trap times are 1000, 3000, 5000, and 9888 hours (to 1/e of initial ion signal). Except for the longest lifetime of 9888 hr, all the other data reported here were published in [6]. The four long trapping times were measured over an eight-year period.

D. Charge Transfer Relaxation Observations

The long ion trap lifetime presents an opportunity to study interesting phenomena that cause the relaxation of ions in the trap. We investigated the effect of charge transfer relaxations induced by the neutral Hg atoms on the trapped Hg ions. Figure 4 shows a typical Rabi curve measured at a low background of neutral Hg, and Figure 5 shows the Rabi curve measured at a high background of neutral Hg. The background neutral fluorescence values obtained for these curves are 220 k and 505 k, respectively. An increase in neutral background of a factor of 2 reduces the signal size approximately by the same factor, giving a direct measure of the effect of neutral Hg on signal size. This reduction in signal size is due to the charge transfer interactions that occur between the trapped ions and the background neutral Hg atoms [9,10]:

$$Hg + Hg^{+} \rightarrow Hg^{+} + Hg. \quad (1)$$

When a collision occurs, the Hg^{+} ion in the trap is instantly relaxed to the unpumped state.

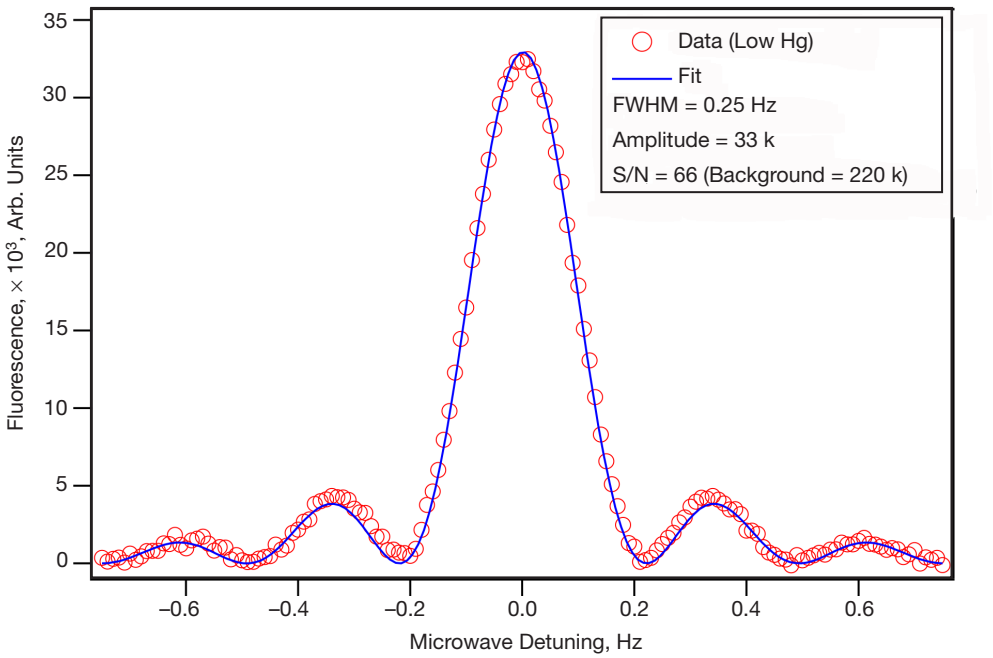

Figure 4. Rabi curve obtained in the condition of lower background neutral Hg.

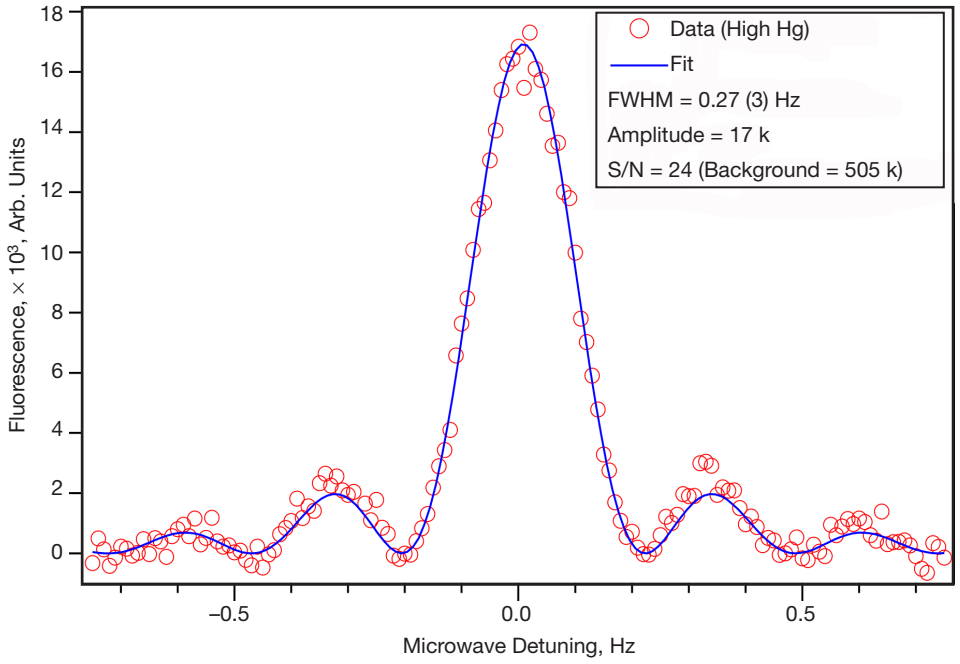

Figure 5. Rabi curve obtained in the condition of a high background neutral Hg.

The temperature-dependent resonant charge exchange collision cross-section, $\sigma_{res}(\epsilon)$, between neutral Hg and an Hg ion can be estimated from the equation [11]:

$$\sigma_{res}(\epsilon) = \sigma_{res}(\epsilon_1)\left[1 + a.ln\left(\frac{\epsilon_1}{\epsilon}\right)\right]^2 \quad (2)$$

where $\sigma_{res}(\epsilon_1)$, a, and ϵ_1 are the positive coefficients and the values for Hg–Hg^+ collision are 164×10^{-16} cm^2, 0.052, and 1 eV, respectively [11]; ϵ is the kinetic energy depending on the vapor temperature in eV. For our case, at a temperature of 343 K the mean relative velocity of atoms is 191 m/s and the energy equivalent to thermal velocity is 0.037 eV. Using the values in Equation 2, we get the calculated resonant collision cross-section to be 2.25×10^{-14} cm^2.

In our setup, there is no option to directly measure the neutral Hg density. However, one can estimate for the collision rate, Γ_{coll}, between Hg–Hg^+ as a function of neutral Hg pressure by using the equation [12]:

$$\Gamma_{coll} = L_0.\bar{\upsilon}.\sigma_{res}(\epsilon).\frac{P_{Hg}}{P_{Atm}} \quad (3)$$

where L_0 (= 2.686 7774(4) $\times 10^{25}$ m^{-3} at 0 deg C and 1 atm.) is the Loschmidt's constant, $\bar{\upsilon} = \sqrt{8.k_B.T/\pi\mu}$ is the mean relative velocity between Hg and Hg^+, P_{Atm} is the atmospheric pressure (760 Torr) and P_{Hg} is the Hg pressure in Torr; k_B is the Boltzmann constant, T is the temperature of Hg vapor and μ is the reduced mass of the collision species (Hg in our case = 3.3×10^{-25} kg). For instance, if we assume an Hg pressure change of 1×10^{-8} Torr, the charge transfer collision rate between neutral Hg and Hg-ion is 16 s^{-1}.

The above analysis shows that the effect is sensitive to the Hg neutral density. Therefore, the consequence of the reduction in the resonant line-Q and S/N affects the clock's short-term stability. Since the ion lifetime is exceptionally long, one can operate the package at low Hg vapor pressure. With these measurements, it is evident that lower vapor pressure of Hg is better for the clock operation. Consideration of the charge transfer relaxation phenomenon is of great value for improving the Hg^+ clock performance as well as for fundamental physics process investigations.

V. Conclusion

The long vacuum integrity and long shelf life of an Hg ion-trap system was presented. The excellent trap lifetimes of more than 400 days (9888 hr) with only a getter-pumped trap package was demonstrated for over 9 years of sealed vacuum. Furthermore, the unique environment of extremely long trap lifetimes was utilized to study the charge transfer relaxation between the trapped Hg ions and the background neutral Hg atoms. These studies are important in view of future portable Hg standards. The optical pumping time with an old ^{202}Hg lamp and the Rabi signals with S/N ratio of 66 indicating the potential for short-term clock stabilities to 1×10^{-13} level were shown.

Acknowledgment

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